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Before the House Science Committee
Honorable Sherwood L. Boehlert, Chairman

February 2, 2005

Mr. Chairman, distinguished committee members and staff:

I am pleased to have the opportunity to share with you the findings of a recent Aerospace Corporation assessment of robotic servicing alternatives for the Hubble Space Telescope. Before I begin, I would like to present an overview of Aerospace and how we came to provide this study for NASA.

The Aerospace Corporation

The Aerospace Corporation is a private, nonprofit corporation, headquartered in El Segundo, California. It was created in 1960 at the recommendation of Congress and the Secretary of the Air Force to provide research, development and advisory services to the U.S. government in the planning and acquisition of space, launch and ground systems and their related technologies. The key features of Aerospace are that we provide a stable, objective, expert source of engineering analysis and advice to the government, free from organizational conflict of interest. We are focused on the government's best interests, with no profit motive or predilection for any particular design or technical solution.

As its primary activity, Aerospace operates a Federally Funded Research and Development Center sponsored by the Under Secretary of the Air Force, and managed by the Space and Missile Systems Center in El Segundo, California. Our principal tasks are systems planning, systems engineering, integration, flight readiness verification, operations support and anomaly resolution for the DoD, Air Force, and National Security Space systems. Through our comprehensive knowledge of space systems and our sponsor's needs, our breadth of staff expertise, and our long term, stable relationship with the DoD, we are able to integrate technical lessons learned across all military space programs and develop systems-of-systems architectures that integrate the functions of many separate space and ground systems.

The Aerospace Corporation also undertakes projects for civil agencies that are in the national interest. Such projects contribute to the common good of the nation while broadening the knowledge base of the corporation. Aerospace has supported many NASA assessments of human and robotic space programs, addressing technical, cost and schedule risks.

Aerospace does not compete with industry for government contracts, and we do not manufacture products. The government relies on Aerospace for objective development of pre-competitive system specifications, and impartial evaluation of competing concepts and engineering hardware developments, to ensure that government procurements can meet the military user's needs in a cost-and-performance-effective manner.

Aerospace employs about 3,450 people, of whom 2,400 are scientists and engineers with expertise in all aspects of space systems engineering and technology. The professional staff includes a large majority, 74%, with advanced degrees, with 29% holding Ph.Ds. The average experience of Members of the Technical Staff (MTS) is more than 25 years. We recruit more than two-thirds of our technical staff from experienced industry sources and the rest from new graduates, university staff, other nonprofit organizations, government agencies, and internal degree programs.

In January of 2004, NASA Administrator Sean O'Keefe announced the cancellation of one last planned space shuttle mission to service the Hubble Space Telescope. Under pressure from Congress and the public, NASA agreed to look for alternative ways to extend Hubble's life.

Analysis of Alternatives

NASA requested that The Aerospace Corporation perform a nonadvocate assessment of Hubble Space Telescope (HST) robotic servicing alternatives. These alternatives encompassed a broad range of options in the following families: ground life extension, disposal, rehosting instrumentation on other platforms, robotic servicing, and the baseline Shuttle Servicing Mission 4 (SM4) previously planned for 2005. In developing this Analysis of alternatives (AoA), Aerospace assessed each alternative against a set of measures of effectiveness (MOEs), which included cost, schedule, risk, and the resulting capability of the alternative to perform science relative to the planned post-SM4 baseline.

The key findings of this AoA are:

- Ground-based life extension does not replace instruments and does not address the risk associated with uncontrolled HST reentry.
- Disposal-only alternatives have relatively low cost, but provide no HST life extension or added science capability comparable to the current configuration.
- Rehost alternatives provide higher value at equivalent cost to the robotic servicing missions, but may result in a two- to seven-year science gap. This higher value results from the lower development and mission risks.
- Robotic servicing alternatives, based on estimated development schedules, are susceptible to arriving too late. HST may no longer be in a serviceable state. Furthermore, they are subject to an aging observatory that may fail for some other reason during the three years following servicing.
- SM4 has costs in the same range as the rehost and robotic servicing alternatives, has higher probability of mission success than the robotic servicing missions, and does not suffer from the gap in science associated with rehost alternatives.[1] Other means to perform SM4 with reduced risk by launching a safe habitat or relocating HST to the vicinity of the International Space Station (ISS) were examined, but would require more development time and be more costly.

Introduction

The Hubble Space Telescope (HST), launched in 1990, is the first and most widely known of NASA's great observatory missions. Orbiting the Earth at an altitude of 320 nautical miles, HST is the only orbiting observatory outside the Earth's atmosphere with the capability to observe simultaneously in the near-IR, visible, and ultraviolet wavelengths. HST observing sensitivity is beyond what is achievable, in most cases, with Earth-based telescopes, and its achievable angular resolution equals or surpasses state-of-the-art ground-based facilities. During its lifetime, HST has produced detailed images of stars, galaxies, and nebulae that have led to major scientific discoveries in astronomy and astrophysics, and have captured the public's imagination with spectacular views of the universe.

[1] SM4 was not analyzed by the study team but was included for completeness as a baseline for comparison. SM4 and the safe habitat approaches have unique human spaceflight risks that were beyond the scope of this study and therefore not assessed. Furthermore they would compete against the ISS shuttle manifest.

HST, whose subsystems and instruments were designed to be serviced on-orbit by astronauts using the space shuttle, has been visited four times for this purpose (Servicing Missions 1, 2, 3A, and 3B). The previous shuttle servicing missions have accomplished a broad array of repairs and upgrades, including the change-out and installation of newer, more capable instruments, replacing solar arrays, batteries, and flight computers, and adding new radiators and thermal shielding.

The next space shuttle servicing mission, Servicing Mission 4 (SM4), was scheduled for 2005 and manifested to replace the Corrective Optics Space Telescope Axial Replacement (COSTAR) and Wide Field Planetary Camera 2 (WFPC2), with the Cosmic Origins Spectrograph (COS) and Wide Field Camera 3 (WFC3), respectively. SM4 would also further extend the observatory's mission life by replacing failed components and those components approaching their end of life.[2] Due to safety concerns surrounding the loss of the space shuttle *Columbia* and crew, NASA cancelled future shuttle flights to HST and embarked on a process to assess other options in order to understand the implications of HST's possible eventual demise, including that of an uncontrolled reentry. NASA's Goddard Space Flight Center (GSFC) took the lead in developing a non-shuttle-based servicing approach, using robotic technologies. This concept, known as the Hubble Space Telescope Robotic Servicing and Deorbit Mission (HRSDM), employs robotic vehicles to accomplish the major servicing elements of the cancelled SM4.

In this context, NASA requested that The Aerospace Corporation prepare a nonadvocate assessment of HST servicing alternatives. These alternatives encompass a broad range of options including doing nothing at all, minimal replacement of components close to failure, partial and full replacement of old instruments, rehosting the existing SM4 replacement instruments or equivalent on other spacecraft, and providing a safe habitat in the vicinity of HST so that an astronaut-performed mission might be reconsidered. Each alternative was assessed against a set of measures of effectiveness (MOEs), which included cost and schedule, risk, and the resulting capability of HST to perform science relative to the planned post-SM4 baseline capability. The capability impact assessment did not address science quality or value, nor did it address how that science might be impacted by constraints imposed by various alternatives. It was assumed that the science value of each instrument has already been assessed as part of the instrument selection process. The capability impact assessment findings were made available to the Office of Space Science Effectiveness Team (OSSET) for comments on the impact on science value from each alternative.

The study team began with research into HST design and servicing history. Next, the team considered a broad array of alternative servicing approaches that spanned the spectrum of options covered by the study. Finally, the team grouped and consolidated similar alternatives into a final set of 21 alternatives that were representative of the trade space to be examined. The 21 alternatives provided natural incremental changes in the complexity of servicing operations and in capability enhancement. A number of robotic alternatives that bounded the trade space were included in the set, including a minimum mass alternative to deorbit HST, and an alternative that provided power and gyro augmentation with and without a robotic arm used for a grapple-assisted docking. More complex alternatives, such as one that accomplished the goals of the GSFC HRSDM, and an ambitious mission to accomplish all of the tasks from SM4, were also included. Each alternative included a component to deorbit HST at the end of its

[2] In addition to COS and WFC3, SM4 was to replace the gyros, batteries, fine guidance sensors (FGS), and install the aft shroud cooling system (ASCS) and thermal protection material.

useful life. The alternatives were described with sufficient detail to allow evaluation and comparison with other alternatives.

In parallel with the development of alternatives, MOEs were defined, in terms of cost and schedule, risk, and capability impact. Cost and schedule MOEs examined absolute cost and development time, as well as cost risk and schedule risk. The risk MOEs included development risk and also the probability of mission success, assuming the alternatives could be successfully developed. The capability impact MOE was defined as the estimated HST instrument capability associated with each of the alternatives.

A measure for safety was also defined early in the study as the mission risk weighted reentry casualty expectation. This measure, however, turned out not to be a strong discriminator among alternatives, and is therefore not included in this report. For cases where the disposal mission is successful, the reentry casualty expectation is zero. Without the disposal mission, the casualty expectation is approximately 1 in 250.

Description of Alternatives

The HST study trade space examined is illustrated in Figure 1. Alternatives were defined in four broad categories: rehost, disposal, service, and safe habitat. Rehost alternatives flew the COS and/or WFC3 instruments on new platforms. Disposal and service alternatives were accomplished by robotic means. Safe habitat referred to a shuttle-based astronaut-servicing mission in concert with an astronaut safe habitat in the vicinity of HST. Because of recently imposed constraints on crewed servicing since the *Columbia* accident, emphasis was placed on robotic servicing and deorbit concepts.

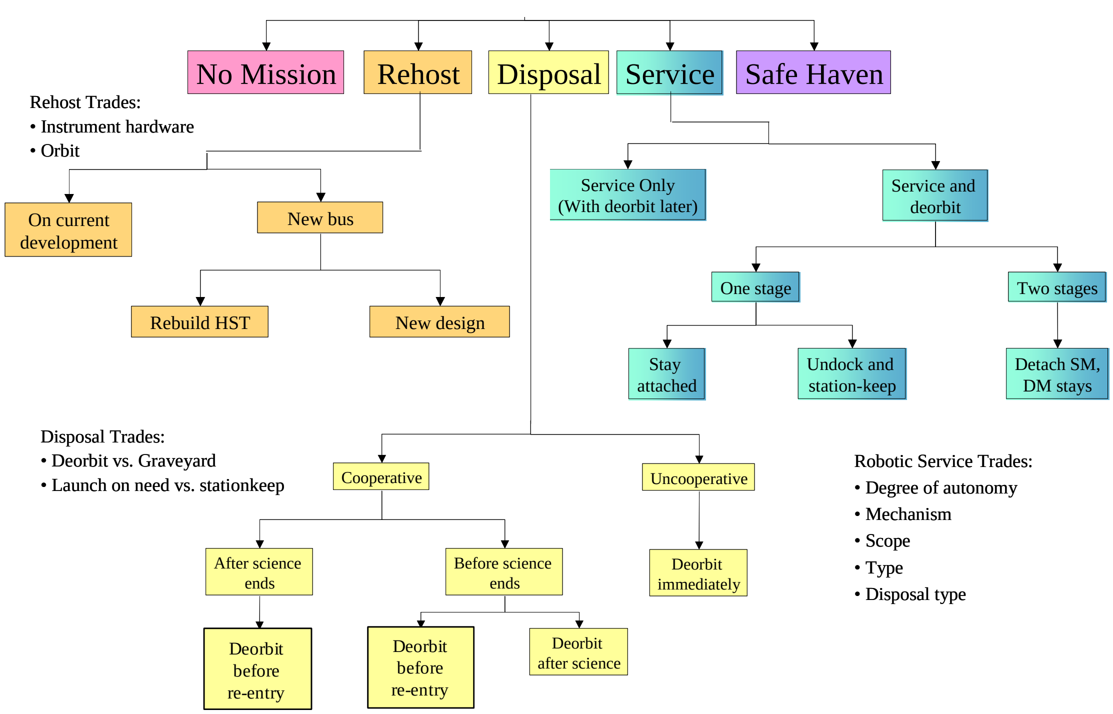

Figure 1. HST Study Decision Tree.

In defining specific alternatives, the study team sought a reasonable coverage of the trade space such as lowest-cost alternatives, alternatives that left the minimum residual mass attached to HST, minimal complexity alternatives, and high complexity alternatives in terms of number and type of operations required. The in-depth feasibility assessment of the alternatives was not performed as part of this study. However, a screening of the alternatives was performed to rule-out unrealistic alternatives. Key trades that manifest themselves in the MOEs are whether a robotic arm is used to assist in docking a deorbit or servicing module and the number and type of servicing operations performed.

The decision tree analysis in Figure 1 led to the following arrangement of alternatives (note that all but the “do nothing” alternative include a deorbit mission):

Alternative family A: Extension of HST through non-servicing means.

- A1: Maintain HST through ground-based life-extension workarounds, until end of life.
- A2: Rehost replacement instruments on a new platform in low Earth orbit (LEO), and deorbit HST.
- A3: Rehost replacement instruments or develop equivalent capability on a new platform beyond LEO, and deorbit HST.

Alternative family B: Robotic missions.

- B1: Robotic docking and disposal of HST without servicing.
- B2: Robotic docking and minimal servicing of life extension only, by addition of an external power and gyro system, followed at end of life by a separate deorbit mission.
- B3: Life extension and instrument replacement servicing alternatives, of varying complexity, combined with a deorbit mission.
- B4: Life extension and instrument replacement servicing alternatives, of varying complexity, followed at end of life by a separate deorbit mission.

Alternative family C: Astronaut safe habitat missions.

- C1: Relocate HST to the vicinity of the ISS to provide a safe habitat for a shuttle-based astronaut-servicing mission.
- C2: Launch a habitat module to the HST orbit, to provide a safe habitat for a shuttle-based astronaut-servicing mission.

Alternative family D: Original Shuttle Servicing Mission 4.

- D1: Proceed with originally planned SM4.

Table 1 provides a summary of each of the 21 alternatives. SM4 was not analyzed as part of this study; however, it was included in the findings for comparison. Data for the cost and schedule estimates for SM4 were provided directly by NASA, and are unofficial, predecisional estimates.

ALTERNATIVE		TASK/COMPONENT											
		Propulsion	Docking	Arm	Battery	Gyro	WFC3	COS	FGS	A, N & D	Disposal	Orbit	FAMILY
Ground Life Extension	A1-A											L	
Rehost COS LEO	A2-A	B	U					X	X		X	L	REHOST
Rehost COS & WFC3 LEO	A2-B	B	U				X	X	X		X	L	REHOST
Rehost COS outside LEO	A3-A	B	U					X	X		X	O	REHOST
Rehost COS & WFC3 outside LEO	A3-B	B	U				X	X	X		X	O	REHOST
De-orbit	B1-A	B	U								X	L	DISPOSAL
De-orbit with Arm	B1-B	B	A	G							X	L	DISPOSAL
Electric Graveyard	B1-C	E	U								X	L	DISPOSAL
Tumbler	B1-D	M	U								X	L	DISPOSAL
Servicer Light	B2-A	M/B	U/T		X	X					X	L	
Baseline no COS	B3-A	M	A	D	X	X	X				X	L	SERVICE
Baseline	B3-B	M	A	D	X	X	X	X			X	L	SERVICE
Baseline with FGS	B3-C	M	A	D	X	X	X	X	X		X	L	SERVICE
Baseline no COS with FGS	B3-D	M	A	D	X	X	X		X		X	L	SERVICE
Cadillac	B3-E	M	A	D	X	X	X	X	X	X	X	L	SERVICE
Boomerang	B4-A	M	A	D	X	X	X	X	X	X	X	L	
Baseline separate deorbit	B4-B	M	A/T	D	X	X	X	X			X	L	
Cling-on	B4-C	M	A	D	X	X	X	X			X	L	
Tug to ISS	C1	E	U								X	L	ASTRONAUT
Safe habitat	C2										X	L	ASTRONAUT
Servicing Mission 4	D1										X	L	

M = Monoprop, B = Biprop, E = ElectricProp
U = Untargeted docking, T = Targeted docking, A = Grapple arm assisted
D = Dexterous arm, G = Grapple arm
L = LEO, O = Outside LEO
X = Includes task/component
A, N & D = Additional SM4 ASCS, NOBL & DMCSU servicing components

Table 1. Summary of Alternatives

Measures of Effectiveness (MOEs)

Each alternative was assessed against a common of set of measures of effectiveness (MOEs), which included cost and schedule, risk, and the observatory capability relative to the post-SM4 state.

The cost MOE (MOE #1) was defined to be the life cycle cost (LCC). The LCC includes (as applicable to the given alternative) servicing and deorbit module development, payload instrument development or modification, spacecraft bus, launch, program management, systems engineering, mission assurance, robotics, ground system development, servicing operations, three years of post-servicing HST mission operations, data analysis, and reserves. Cost estimates were calculated as probability density functions, based on triangular distributions for the main cost elements listed above. The cost MOE was defined as the 75th percentile life cycle cost.

The schedule MOE (MOE #2) was defined to be the development time from program authority to proceed (ATP) to launch. The schedule MOE was based on schedule estimating relationships developed for the rehost, deorbit and robotic servicing, and safe haven option families. Like cost, schedule estimates were also developed as probability distributions for use in the calculation of MOE #3.

Development risk (MOE #3) was the convolution of two probability distribution functions: the probability distribution of HST being in the required state, and the probability distribution of the development time. This convolution resulted in the probability of HST being in the required state when the servicing or disposal mission is launched. For servicing missions, the “required state” was defined as a state where a servicing mission can dock with HST, either cooperatively or uncooperatively, and where HST can be restored to full operations using only the replacement parts associated with the current design of the servicing alternative. For this study, this is essentially a state where gyros may have failed, but all other subsystems necessary for the functioning of HST are operating. For the disposal-only missions, the “required state” was based on HST having not reentered the Earth’s atmosphere.

The probability of mission success (MOE #4) is a measure of mission risk, and is based on the probability of successfully completing a sequence of events, beginning at launch and including proximity operations and docking, the sequence of servicing steps, three years of HST mission operations, and deorbit. This measure is independent of development risk. In the analysis process, there is no linkage between systematic or workmanship errors that may occur prelaunch during development, but that manifest themselves later during the mission.

The capability MOE (MOE #5) measures the predicted capability of the HST to perform science relative to its expected post-SM4 condition. There is no metric for future space exploration value and no weight is given to the value of one particular scientific investigation relative to another.

Summary of Results

Figure 2 shows MOE #1 (life cycle cost) for the alternatives examined. The numbers following the bars provide the range of costs within each alternative family. In all cases, it is assumed that each system is a new development. However, for consistency, each alternative is credited with heritage for about 40 percent of the component mass of the system. Not unexpectedly, the astronaut-servicing missions that depend on a safe habitat (alternative family C) are the costliest; while the disposal alternatives (alternative family B1) are the least expensive. Note also that there is little difference between the cost of the rehost alternatives and the robotic servicing missions. The discriminator becomes risk, which will be discussed in the sections that follow.

The rehost alternatives range in cost from $1.9B to $2.3B, with roughly $350M of that total reserved for the HST deorbit mission (represented by B1-A). The disposal missions have the greatest variability in cost, ranging from $300M for the simplest deorbit alternative, B1-D, to $1.1B for the B1-B alternative that uses grapple-arm-assisted docking. Drivers on the range of B1 family costs are whether a robotic arm is utilized, estimated at approximately $300M, with the associated mass needed to support the robotic components on the deorbit module. Additionally, integration of the arm significantly increases program management, systems engineering, and mission assurance (PM/SE/MA) costs over the no-arm option.

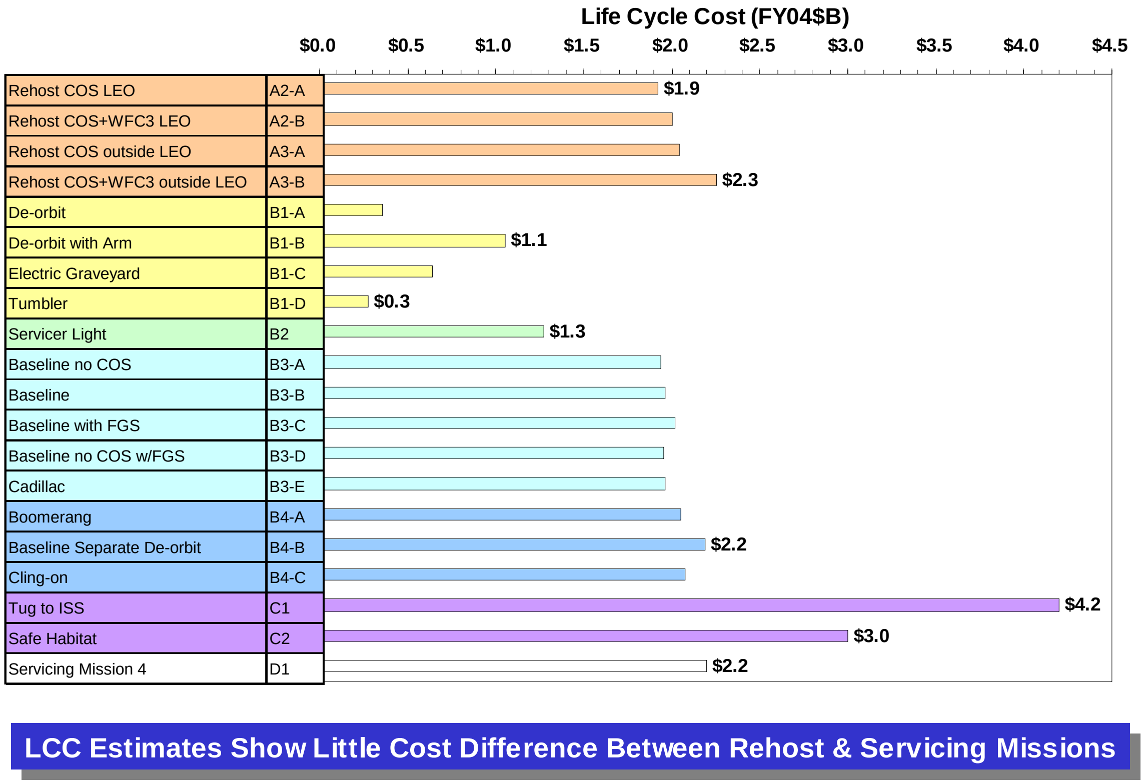

Figure 2. Life Cycle Cost (MOE #1).

For the servicing alternatives, costs range from $1.3B for the external gyro and battery augmentation option, which doesn't require a robotic arm (B2), to $2.2B for alternative B4-B, which uses a second separate mission for deorbit. The cost variations across the B3 family are relatively small since the mass of these options is generally insensitive to the equipment manifested and the servicing steps that need to be accomplished.

The discriminator in the costs for the deorbit and robotic servicing options is the grapple arm. Once the grapple arm is included, adding the capability for a dexterous arm enables a large array of complex servicing tasks at an incremental cost of about $700M over the armless external servicing option, B2. The cost of the robotics was based on the development cost of the Canadarm—Shuttle Remote Manipulator System (SRMS), the European Robotic Arm (ERA) for the Columbus Orbital Facility of the ISS, and the Special Purpose Dexterous Manipulator (SPDM) developed for use on the ISS.

For systems that do not use the grapple arm to dock, there are impacts to the design and implementation of the docking system, the requirement for precision maneuvers, reduced closing velocities, and small docking forces. In the case of a servicing mission, the closing rates and latching forces would be limited so as not to damage HST. However, in the case of unassisted docking for the purposes of deorbit, damage to HST may not be a central issue, and a different approach that allows higher forces to guarantee a hard dock and positive latching might be more appropriate.

Figure 3 displays MOE #2, development schedule, and MOE #3, development risk. The HST predicted lifetime bar at the bottom of Figure 3 is based on two assumptions on the application of the HST reliability model. The “HST Reliability Model” end of serviceable state (EOSS) prediction (50th percentile probability of failure date) is calculated using the current failure rate assumptions in the reliability model. This model has been improved over the years by periodically updating the component failure rates based on actual HST operational data. It has been observed, however, that HST hardware has often lasted longer than predicted even with the periodic updates to the failure rate data. Moreover, the reliability model was originally designed and used to size the interval between servicing missions, and the validity of using the model to predict an end-of-life state has never been fully assessed. Consequently, experts familiar with HST often view the HST reliability model as overly conservative. To address this criticism, a different approach, recommended by NASA GSFC, to updating the failure rates was applied. In this approach, the failure rates for the top five reliability drivers were recomputed based solely on HST operational experience, having the effect of significantly deweighting them in the reliability calculation relative to the standard HST reliability model. This approach adds about 12 months of life to HST (50th percentile) and is labeled “EOSS GSFC Assumptions.”

Serviceable state = HST will be able to be restored to full operations using only the replacement parts associated with the current design of the servicing alternative

		ATP to Launch (months)	Prob HST in Serviceable State
		Nominal	P(Success)
Rehost COS LEO	A2-A	100	N/A
Rehost SM4 LEO	A2-B	101	N/A
Rehost COS outside LEO	A3-A	96	N/A
Rehost SM4 outside LEO	A3-B	97	N/A
De-orbit	B1-A	51	1.00
De-orbit with Arm	B1-B	59	1.00
Electric Graveyard	B1-C	58	1.00
Tumbler	B1-D	47	1.00
Servicer Light	B2	57	0.40
Baseline no COS	B3-A	64	0.38
Baseline	B3-B	64	0.38
Baseline with FGS	B3-C	64	0.38
Baseline no COS w/FGS	B3-D	64	0.38
Cadillac	B3-E	65	0.38
Boomerang	B4-A	66	0.38
Baseline Separate Deorbit	B4-B	64	0.38
Cling-on	B4-C	70	0.37
Tug to ISS	C1	85	0.26
Safe Habitat	C2	39	0.59
Servicing Mission 4	D1	31	0.74

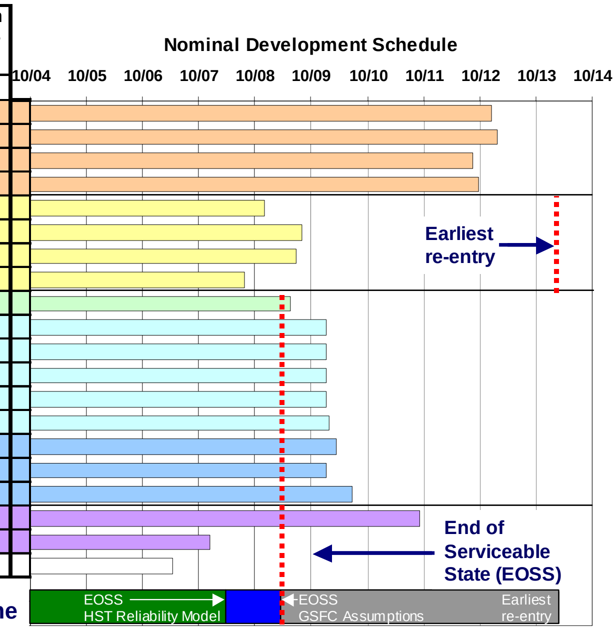

Figure 3. Development Schedule (MOE #2) and Development Risk (MOE #3).

As can be seen in Figure 3, the nominal development time exceeds the date associated with the end of serviceable state by a number of months in most cases. The B2 servicing option nominal development time almost meets this date. The probability of HST being in a serviceable state is less than or equal to 40 percent for the robotic servicing options, because they are tied to a HST demise in April 2009. The deorbit alternatives are tied to the earliest reentry date of 2014, and can be developed within this time with a very high likelihood.

The rehost options are also insensitive to the HST date of demise. However, there is a high likelihood that the rehost options cannot be developed before the HST end of life, resulting in a multiyear science gap with no HST-like observing capability in orbit.

The development risk for the SM4 alternative is listed at 74 percent. This calculation is based on the earliest launch date provided by NASA, which is unofficial and predecisional. In assigning the SM4 launch date, NASA assumed that the SM4 mission, if it were to fly, would be launched

31 months from the ATP date of October 2004. Conceivably, the mission could be moved forward in the return-to-flight schedule, which would decrease the development risk, with the constraint that sufficient astronaut training time be provided.

Figure 4 presents the probability of mission success (MOE #4), and provides an example calculation of this value for the baseline alternative, B3-B. The definition of mission success is different for each alternative and is dependent on the number of events that must be accomplished to achieve the final success state. For all robotic servicing alternatives, the success state includes three years of science operations and a successful deorbit. Clearly, there are more events that could lead to mission failure for servicing missions than for disposal missions. Hence, they tend to have a lower probability of mission success by their very nature. As can be seen in the B3-B example shown in Figure 4, the probability of mission success for the robotic servicing missions is dominated by the probability of successfully completing the servicing operations and by the probability of HST operating for three years, once the servicing is complete. Due to the age of the HST, after several years of post-service operations, other components and failure mechanisms begin to dominate the reliability estimates.

		Mission (Serv, Sci, Dispose)
		P(Success)
Rehost COS LEO	A2-A	0.83
Rehost SM4 LEO	A2-B	0.83
Rehost COS outside LEO	A3-A	0.80
Rehost SM4 outside LEO	A3-B	0.80
De-orbit	B1-A	0.89
De-orbit with Arm	B1-B	0.93
Electric Graveyard	B1-C	0.88
Tumbler	B1-D	0.87
Servicer Light	B2	0.58
Baseline no COS	B3-A	0.58
Baseline	B3-B	0.52
Baseline with FGS	B3-C	0.48
Baseline no COS w/FGS	B3-D	0.54
Cadillac	B3-E	0.32
Boomerang	B4-A	0.26
Baseline Separate Deorbit	B4-B	0.47
Cling-on	B4-C	0.52
Tug to ISS	C1	0.43
Safe Habitat	C2	0.63
Servicing Mission 4	D1	0.63

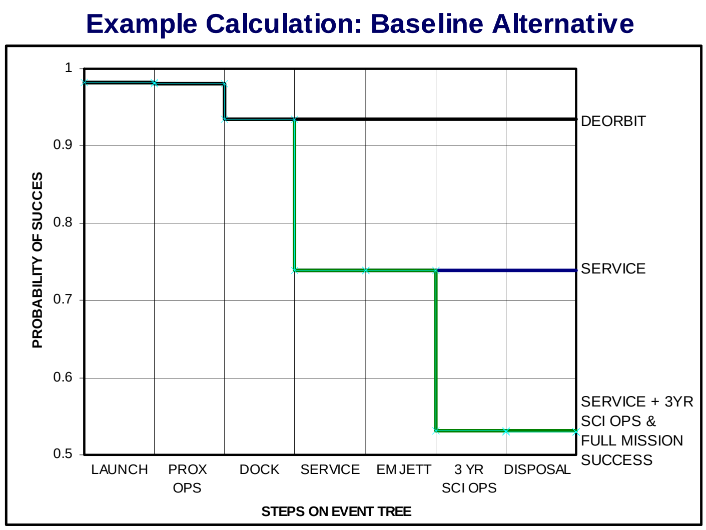

Figure 4. Probability of Mission Success (MOE #4).

Note the 63 percent probability of mission success for the SM4 alternative. Astronaut servicing has been successfully demonstrated on four prior servicing missions. Probability of success for the servicing events is 100 percent. The shuttle has failed once on launch and once on reentry, leading to a 99 percent probability of success. Here again, the probability driving the success is achieving three years of post-servicing operations.

Figure 5 provides the capability impact for each alternative relative to the post-SM4 baseline (MOE #5), based on historical instrument utilization patterns. Clearly the disposal options have a resultant relative capability of zero. The B2 alternative, which provides power and rate-sensing augmentation, is also very low since new instruments are not added. Furthermore, in the existing HST architecture, the Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

Cooling System (NCS) is powered through a separate circuit that is not accessible by alternative B2. The result is that the NCS would need to remain operating directly off the HST battery bus, serviced by the HST solar arrays. This may not be possible once the HST batteries reach a state where they can no longer hold sufficient charge to support the NCS load. The rehost alternatives register at 40- or 78-percent of the full post-SM4 capability. This calculation is based on historical utilization data that indicates that new instruments generally crowd out the old instruments for observing time. This measure is imperfect since it does not account for the benefits of observing the same target simultaneously with two or more instruments, increased observing efficiency associated with the rehost alternatives outside of LEO, or the fact that each instrument in a smaller instrument suite may receive higher overall utilization.

			Instruments						
		Capability Relative to Post-SM4 HST	WFPC2	STIS	ACS	NICMOS	WFC3	COS	Family
Rehost COS LEO	A2-A	40%						X	REHOST
Rehost SM4 LEO	A2-B	78%					X	X	
Rehost COS outside LEO	A3-A	40%						X	
Rehost SM4 outside LEO	A3-B	78%					X	X	
De-orbit	B1-A	0%	No value						DISPOSAL
De-orbit with Arm	B1-B	0%							
Electric Graveyard	B1-C	0%							
Tumbler	B1-D	0%							
Servicer Light	B2	21%	X	X	X				
Baseline no COS	B3-A	62%		X	X	X	X		SERVICING
Baseline	B3-B	100%		X	X	X	X	X	
Baseline with FGS	B3-C	100%		X	X	X	X	X	
Baseline no COS w/FGS	B3-D	62%		X	X	X	X		
Cadillac	B3-E	100%		X	X	X	X	X	
Boomerang	B4-A	100%		X	X	X	X	X	
Baseline Separate Deorb	B4-B	100%		X	X	X	X	X	
Cling-on	B4-C	100%		X	X	X	X	X	
Tug to ISS	C1	100%		X	X	X	X	X	OTHER
Safe Habitat	C2	100%		X	X	X	X	X	
SM4	D1	100%		X	X	X	X	X	

Figure 5. Capability Relative to Post-SM4 HST (MOE #5).

Since the capability metric is based solely on instrument utilization, all alternatives that result in the same final instrument complement as the post-SM4 configuration were scored 100 percent. There are additional servicing items accomplished by SM4, such as the installation of the ASCS radiator on the external shroud to provide additional instrument detector thermal margin/control and improve HST's operational efficiency. This may provide a capability benefit through additional observing time; however, enhancements of this nature are not captured in this metric.

Figure 6 summarizes the five major MOEs assessed in this study: cost, development time, development risk, mission risk, and capability impact. Mission risk and development risk are rated with qualitative descriptors. The uncertainty of the risk assessments for the robotic servicing alternatives is higher than for the deorbit missions and the rehost options. While there are several missions yet to be launched that have features similar to the robotic servicing alternatives (autonomous docking using grapple arms, proximity operations, etc.), none have flown, and they are outside the historical experience base. For this reason, it is difficult to discriminate between the risks associated with any of the robotic servicing alternatives when the development and mission risks (one minus the probability of success) cluster in the 40- to 60-percent range.

		Cost & Schedule		Risk & Safety		Capability						
Alternatives		**Life Cycle Cost (FY04$B)**	**Nominal Development Time (Years)**	**Development Risk**	**Mission Risk**	**WFPC2**	**STIS**	**ACS**	**NICMOS**	**WFC3**	**COS**	**Family**
Ground Life Extension	**A1**					**X**	**X**	**X**	**X**			
Rehost COS LEO	**A2-A**	**$1.9**	**8.4**	**Science Gap**	**Low**						**X**	**REHOST**
Rehost SM4 LEO	**A2-B**	**$2.0**	**8.4**							**X**	**X**	
Rehost COS outside LEO	**A3-A**	**$2.0**	**8.0**								**X**	
Rehost SM4 outside LEO	**A3-B**	**$2.3**	**8.1**							**X**	**X**	
De-orbit	**B1-A**	**$0.4**	**4.2**	**Low**	**Low**	**No value**						**DISPOSAL**
De-orbit with Arm	**B1-B**	**$1.1**	**4.9**									
Electric Graveyard	**B1-C**	**$0.6**	**4.8**									
Tumbler	**B1-D**	**$0.3**	**3.9**									
Servicer Light	**B2**	**$1.3**	**4.7**	**High**	**High**	**X**	**X**	**X**				
Baseline no COS	**B3-A**	**$1.9**	**5.4**	**High**	**High**		**X**	**X**	**X**	**X**		
Baseline	**B3-B**	**$2.0**	**5.4**				**X**	**X**	**X**	**X**	**X**	
Baseline with FGS	**B3-C**	**$2.0**	**5.4**				**X**	**X**	**X**	**X**	**X**	
Baseline no COS w/FGS	**B3-D**	**$2.0**	**5.4**				**X**	**X**	**X**	**X**		**SERVICING**
Cadillac	**B3-E**	**$2.0**	**5.4**				**X**	**X**	**X**	**X**	**X**	
Boomerang	**B4-A**	**$2.1**	**5.5**	**High**	**High**		**X**	**X**	**X**	**X**	**X**	
Baseline Separate Deorb	**B4-B**	**$2.2**	**5.4**				**X**	**X**	**X**	**X**	**X**	
Cling-on	**B4-C**	**$2.1**	**5.8**				**X**	**X**	**X**	**X**	**X**	
Tug to ISS	**C1**	**$4.2**	**7.1**	**High**	**Hign**		**X**	**X**	**X**	**X**	**X**	**OTHER**
Safe Habitat	**C2**	**$3.0**	**3.3**		**Medium**		**X**	**X**	**X**	**X**	**X**	
SM4	**D1**	**$2.2**	**2.6**	**Medium**	**Medium**		**X**	**X**	**X**	**X**	**X**	

Figure 6. HST Servicing Study Results Summary.

A qualitative, but uncalibrated scale was selected to bin the mission risk values into the "low," "medium," and "high" risk categories. In general, mission success probabilities higher than 80 percent were labeled low risk. Success probabilities between 80 percent and 40 percent were labeled medium risk, and success probabilities below 40 percent were labeled high risk. For medium-risk alternatives, the mission risk was dominated by the probability of HST operating successfully for three years after the servicing mission is completed. Hence, all astronaut-servicing options, including SM4, have at least medium mission risk. The medium ranking on the SM4 development risk is constrained by the shuttle launch date assumption provided by NASA. In the high-risk category, mission risk was dominated both by the probability of success of the servicing mission, and the probability of success of the three years of operations.

Figure 7 illustrates the results of combining three MOEs—capability (MOE #5), development risk (MOE #3), and probability of mission success (MOE #4)—to produce an expected value calculation:

Expected Value = MOE #3 * MOE #4 * MOE #5

This combined expected value is plotted against life-cycle cost. Figure 7 indicates that the disposal alternatives provide no value relative to observatory capability. The expected value calculation also indicates that rehosting both the SM4 instruments on new platforms provides higher value at equivalent cost to the robotic-servicing missions. This results from the lower development and mission risks, which includes launch and on-orbit operations, associated with the rehost alternatives. There is, however, a gap in science with the rehost alternatives that is not captured in this expected value assessment.

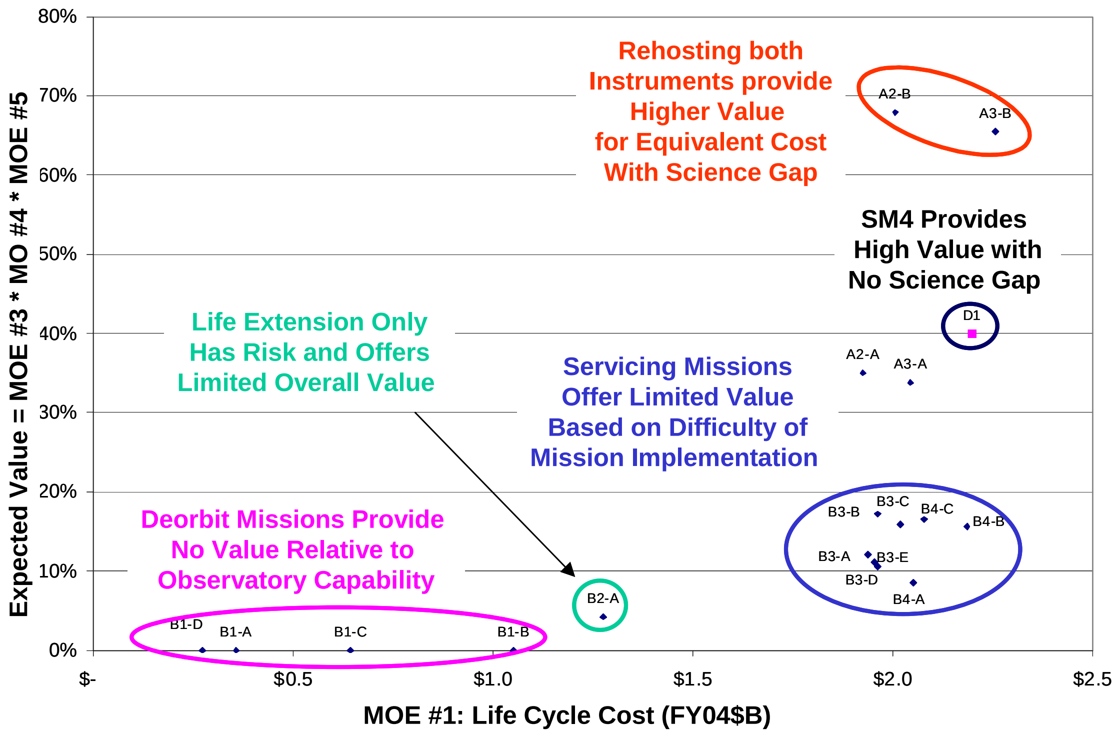

Figure 7. Expected value vs. life cycle cost.

The robotic servicing alternatives cluster in the lower right corner of the plot, suggesting that the value of these alternatives is limited based on difficulty of the mission implementation, the complexity of the servicing mission, and the reliability of HST after servicing.

SM4 has costs in the same range as the rehost and robotic-servicing alternatives. It has the added benefit of higher probability of mission success than the robotic servicing missions, and does not suffer from the gap in science associated with the rehost alternatives.

Acronyms

AoA	Analysis of alternatives
ASCS	Aft shroud cooling system
ATP	Authority to Proceed
CONOPS	Concept of Operations
CORDS	Center for Orbital and Re-entry Debris
COS	Cosmic Origins Spectrograph
COSTAR	Corrective Optics Space Telescope Axial Replacement
DMCSU	Data Management Cross Strap Unit
EOSS	End of serviceable state
ERA	European Robotic Arm
FGS	Fine Guidance Sensor
FY	Fiscal Year
GEO	Geosynchronous Earth orbit
GSFC	Goddard Space Flight Center
HRSDM	Hubble Space Telescope Robotic Servicing and De-orbit Mission
HST	Hubble Space Telescope
ISS	International Space Station
LCC	Life cycle cost
LEO	Low Earth orbit
MOE	Measure of Effectiveness
NCS	NICMOS Cooling System
NICMOS	Near Infra-Red Camera and Multi-Object Spectrometer
NOBL	New Outer Blanket Layer
OSSET	Office of Space Science Effectiveness Team
PM/SE/MA	Program management, systems engineering, and mission assurance
SM4	Servicing Mission 4
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
WFC3	Wide Field Camera 3
WFPC2	Wide Field Planetary Camera 2